CATHODIC PROTECTION DESIGN

1-1.   Introduction.

Recently, ceramic coated anodes have been incorporated in
cathodic protection systems. Ceramic or metal-oxide anodes have
been used for cathodic protection since 1971 in Europe and since
1984 in the United States. One of the main advantage of ceramic
anodes are that they are not consumed.

Ceramic anodes consist of various shapes of high purity titanium
substrates with coatings of precious metal oxides tailored to the
environment in which they will be used.

Unlike most other metal oxides (or ceramics), these metal oxides
are conductive. Ceramic anodes are dimensionally stable. The
ceramic coating is already oxidized (corroded).
The current capacity is a function of constituent variables and
is rated by the manufacturers. They have design life
expectancies of up to 20 years at a rated current output. The
life can be extended by a reduction in output current density.
Their life is limited by time and current density. The end of
the ceramic anode life is marked by a chemical change in the
oxide form and a resultant loss in conductivity. Ceramic anodes
are made in a variety of shapes for various applications. Among
these are wire, rods, tubes, strips, discs, and mesh. Ceramic
anodes have excellent ductility, which has eliminated the concern
about mechanical damage during shipment and installation.
Ceramic anodes are also a fraction of the size and weight of
traditional anode materials.

Scratches or other minor physical damages to the coating result
in the formation of an inert and nonconductive oxide of the
substrate (titanium) when operated at less than 60 V in fresh
water and underground applications. If they are installed in
salt or brackish water, the DC design voltage should be limited
to 12 V. The overall function of the anode is not significantly
impaired.

1-2.   Cathodic Protection Design Using Ceramic Anodes.

The following steps are involved in designing a cathodic
protection system using ceramic anodes:

a. Collect data.

Design requirements should be established, and certain
assumptions will be made.

1) History

Information from occupants in the area can indicate
the severity of corrosion problems. Data on failures
and failure rates of nearby structures can be invalu-
able and must be considered.

2) Drawings

Drawings of the structure to be protected and the
area where it is or will be installed are needed to
provide the physical dimensions of the structure for
determining surface area to be protected, and
locations of other structures in the area that may
cause interference, of insulating devices, and of
power sources. Information on coatings should be
obtained.

3) Tests

Current requirement test and potential survey test
results are needed for existing structures that will
be protected. Electrolyte (soil or water) resistivi-
ty tests and evaluation of conditions that could
support sulfate-reducing bacteria are needed for all
cathodic protection designs. This information will
indicate the size of the cathodic protection system
that will be required as well as the probability of
stray current problems. Soil resistivities contrib-
ute to both design calculations and location of the
anode groundbed.

4) Life

The user must determine the required number of years
that the structure needs to be protected, or the
designer must assume a nominal life span. The struc-
ture will begin to deteriorate from corrosion at the
end of the cathodic protection system's design life
unless the system is rejuvenated.

5) Coatings

Cathodic protection complements the protective coat-
ing system. A good coating system substantially
reduces the amount of cathodic protection current
required. The coating efficiency has to be
assumed.

6) Short circuits

All short circuits must be eliminated from both new
and existing structures for which a cathodic
protection system is being designed.

b. Calculate surface area to be protected.

The overall current requirement of a cathodic protection
system is directly proportional to the surface area to be
protected. This includes underground or submerged pipes,
buried tanks, and wetted surfaces (up to high
water(level) of watertanks (including risers).

c. Determine current requirement.

For existing structures, a current requirement test will
provide the actual current requirement at the time of the
test. Allowance should be made in the design for future
degradation of coatings or structure additions that will
increase the current requirement.

For new structures not yet installed, the amount of
current needed to provide protection as defined in Na-
tional Association of Corrosion Engineers (NACE) RP-0l-69
(reference 22) will be dependent on a number of
variables. Table 3-1 gives guidelines for current
requirements in various soil and water conditions.

The efficiency of the coating system, both when new and
at the end of design life, is a determining factor in the
range of current that will be required over the lifetime
of the system. Total current required is given by the
following equation:

$$I = (A)(I')(1.0 - C_E) \hspace{2cm} \text{(eq 1-1)}$$

where I is the total current requirement, A is the total
surface area to be protected, I' is the estimated current
density, and C_E is the efficiency of the coating system.
This procedure should always be followed, even when a

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current requirement test has been performed, as a check on assumptions made. Current density may be estimated from information given in table 3-1.

d. Select anode type.

Ceramic anodes are made in a variety of shapes, such as, wires, rods, tubes, strips, disks, and mesh.

The 0.062-in. diameter anode wire has a 20-year life at a maximum current rating of 115 mA per linear ft in fresh water, 285 mA in salt water, and 170 mA in brackish water. Wire anodes are well suited for applications in water tanks. They are generally not used underground.

Ceramic rod anodes are manufactured bare for aqueous environments and prepackaged for installation in soil. Ceramic rod anodes are produced in diameters of 1/8 in., 1/4 in., 3/8 in. and ½ in. and in standard lengths of 4, 6, and 8 ft, although almost any length can be custom fabricated with self-healing screw connections for field assembly to the desired length, or with permanent, factory-molded, cable-to-anode connections. For underground applications, rods are frequently packaged in 2- or 3-in. diameter steel tubes filled with a high carbon, low resistivity coke breeze. Their small size and high current capacity make rods particularly well suited for both underground shallow and deep anode systems. For marine applications, the rod anode is often encased in a perforated PVC package that provides mechanical protection and prevents the possibility of the anode contacting the protected structure. They are used in a similar manner as high silicon cast iron and graphite anodes.

For long ceramic anode wires and rods, the voltage drop in the titanium substrate must be considered. While titanium is a relatively good metallic conductor, its resistance is approximately 33 times that of copper. The maximum length for solid titanium wire and rod anode applications to assure that uniform discharge of current is achieved in several different environments is provided below:

Maximum Anode Length From Connection Point

Solid Titanium Anodes

Anode Diameter   0.062 in. 0.125 in. 0.250 in.

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ENVIRONMENT	LENGTH (ft)		
Sea Water	3	5	9
Coke Breeze	6	10	20
Fresh Water	30	50	100

Where a specific design requires longer length anodes than
provided for in the above table, the titanium wire or rod
can be provided with a copper core to reduce the effective
resistance. This type of construction has been in use for
over 15 years and has proved to be very durable. The
titanium wall thickness should be a minimum of 20 percent of
the wire or rod diameter (e.g., for 0.062-in. diameter wire,
the titanium wall thickness should be 0.0124 in., minimum)

The maximum allowable length for copper-core titanium wire
and rod anodes is provided in the table below:

Maximum Anode Length From Connection Point

Copper Cored Titanium Anodes

Anode Diameter   0.062 in.   0.125 in.   0.250 in.

ENVIRONMENT	LENGTH (ft)		
Sea Water	7	12	24
Coke Breeze	12	24	54
Fresh Water	70	135	300

A strip anode is presently manufactured as a 3- or 7-ft bar
of ceramic-coated substrate, molded into a multilayer
composite of fiberglass-reinforced plastic (FRP) and
polyurethane 4 or 8 ft long and 4 in. wide that provides
impact resistance, mechanical support, and electrical
insulation.

A mesh anode is produced using highly expanded titanium
sheet metal and is used where a large area is to be
protected, where area for anode placement is confined, and
where future access is not practicable. Its use under a
structure's base such as an on-grade tank bottom with
secondary membrane containment or select reinforced
concrete bridges, wharfs, etc., would be appropriate.
Because of its size and the nature of its application, mesh
is generally restricted to use in new facilities.

e. Calculate number of anodes (N) or length of bare anode wire (L_B).

1) For required design life

Since ceramic anodes are not consumed during their life, the quantity of ceramic material beyond that required to form a coating is not relevant. The number of anodes or length of anode wire required is determined from the total current required and the manufacturer's published current rating for a given life. For rod, strip, tube and disk anodes:

Number of anodes required =

$$\frac{\text{Total current required}}{\begin{array}{l}\text{Manufacturers rated}\\ \text{current for specific}\\ \text{size, environment and life.}\end{array}} \qquad \text{(eq l-2a)}$$

2) For wire anodes:

Total footage of anode =

$$\frac{\text{Total current requirement}}{\begin{array}{l}\text{Manufacturers rated current}\\ \text{capacity per foot of wire}\\ \text{for a given environment and life.}\end{array}} \qquad \text{(eq l-2b)}$$

The number calculated will determine the minimum number of anodes or anode wire length required.

f. Calculate the total circuit resistance (R_T).

The total circuit resistance (R_T) consists of the anode-to-electrolyte resistance (R_N) plus the interconnecting wire resistance (R_W) plus the structure-to-electrolyte resistance (R_C).

$$R_T = R_N + R_w + R_C \qquad \text{(eq 1-3)}$$

A criterion of 2-ohm maximum groundbed resistance is often used to limit the rectifier output voltage and the associated hazards of overprotection. When the total required current is low, a higher total resistance is often

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acceptable. As the required current increases, the total resistance should be reduced. See table 3-10.

The total anode-to-electrolyte resistance (R_N) is calculated in different ways according to the type of anode installation. The anode-to-electrolyte resistance for a <u>single</u> anode is given by R_A.

For a single vertical anode:

$$R_A = \frac{(0.0052) \quad p}{(L)} [\ln (8L/d) - 1] \qquad \text{(eq 1-4)}$$

Where R_A is the anode-to-electrolyte resistance for a single anode, p is the electrolyte resistivity in ohm-cm, L is the length of the backfill column in feet, and d is the diameter of the backfill column in feet.

It should be noted that the anode dimensions are the over-all length and diameter including backfill, if the backfill is coke breeze and is not significantly more than 2 ft longer than the anode or not significantly more than 20 ft longer than the anode column in a deep vertical groundbed configuration. For earth backfill, the backfill column dimensions should be the dimensions of the manufacturer's standard packaged anode can. Bare ceramic anodes shall not be installed in ground without coke breeze backfill. Coke breeze allows venting of gases and effectively reduces R_A.

If vertical anode dimensions are assumed to be 6 in. in diameter and 8 ft in length, the following empirical relations may be used:

$$R_A = \frac{p}{398} \qquad \text{(eq 1-5)}$$

If the anode dimensions are different, a different empirical relation may be used:

$$R_A = \frac{p \ K}{L} \qquad \text{(eq 1-6)}$$

where R_A is the anode-to-electrolyte resistance, p is the electrolyte resistivity in ohm-cm, L is the length of the backfill column in feet, and K is a shape function that is selected from table 3-4.

Deep anode groundbed resistance graphs are available for deep vertical ground beds. (See figure 2-9a through 2-9c located in section 2-4.)

For a single horizontal anode:

$$R_A = \frac{(0.0052)\ p}{L}\ [\ln\frac{4L^2 + 4L\ \sqrt{(2h)^2 + L^2}}{2\ d\ h} \qquad (eq\ 1\text{-}7)$$

$$+\ \frac{2\ h}{L}\ -\ \frac{\sqrt{(2\ h)^2 + L^2}}{L}\ -\ 1]$$

where R_A is the anode-to-electrolyte resistance in ohms, p is the electrolyte resistivity in ohm-cm, L is the length of the backfill cylinder in feet, d is the diameter of the backfill cylinder in feet, and h is the depth of the backfill cylinder in feet.

If the horizontal anode dimensions are assumed to be 6 in. in diameter, 8 ft long, and buried 6 ft below the surface, the following empirical expression may be used.

$$R_A = \frac{p}{441} \qquad (eq\ 1\text{-}8)$$

where R_A is the anode-to-electrolyte resistance in ohms and p is the electrolyte resistivity in ohm-cm.

For multiple vertical anodes:

$$R_N = \frac{(0.0052)\ p}{N\ L}\ [(\ln\ (8L/d)\ -1)$$

$$+\ \frac{2\ L}{C_c}\ \ln\ (.656\ N)) \qquad (eq\ 1\text{-}9)$$

where R_N is the anode-to-electrolyte resistance, p is the electrolyte resistivity in ohm-cm, N is the number of anodes, L is the length of the backfill column in feet, d is the diameter of the backfill column in feet, and Cc is the center-to-center spacing of the anodes in feet. This equation assumes a linear configuration of the groundbed anodes.

If the number of anodes used does not produce a low enough anode-to-electrolyte resistance, the number of anodes will have to be increased accordingly.

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For optimum results, the length of the backfill column (L) should be less than the anode spacing (C_c).

If multiple anodes are assumed to be 6 in. in diameter and 8 ft long, the following empirical expression may be used:

$$R_N = \frac{p \ F_{ADJ}}{398} \qquad \text{(eq 1-10)}$$

where R_N is the anode-to-electrolyte resistance in ohms, p is the electrolyte resistivity in ohm-cm and F_{ADJ} is selected from table 3-9, which compensates both for the number and spacing of the anodes, which will be connected together as one groundbed.

If the anode dimensions are different, another empirical expression may be used:

$$R_N = \frac{R_A}{N} + \frac{p \ P_F}{C_c} \qquad \text{(eq 1-11)}$$

where R_N is the anode-to-electrolyte resistance, R_A is the anode-to-electrolyte resistance for a single anode, p is the soil resistivity in ohm-cm, N is the number of anodes used, P_F is a paralleling factor selected from table 3-5, and Cc is the center-to-center spacing of anodes in feet. This equation assumes a linear configuration of the groundbed anodes.

For multiple horizontal anodes:

$$R_N = \frac{p \ F_{ADJ}}{441} \qquad \text{(eq 1-12)}$$

where p is the electrolyte resistivity in ohm-cm and F_{ADJ} is an adj3sting factor for groups of anodes selected from table 3-9.

For a circle of rod anodes (as in a water storage tank):

where R_N is the anode-to-electrolyte resistance, p is the electrolyte resistivity in ohm-cm, L_B is the length of each

$$R_N = \frac{0.0052 \ x \ p \ x \ \ln \ [D/2 \ A_R \ x \ D_E)]}{L_B} \qquad \text{(eq 1-13)}$$

rod anode in feet, D is the tank diameter in feet, A_R is the radius of the anode circle in feet, and D_E is an equivalent diameter factor from figure 2-17.

For wire anode circle or hoop (in a water storage tanks):

$$R_N = \frac{0.0016 \ p}{D_R} \ (\ln \ \frac{8D_R}{D_A} + \ln \ \frac{2 \ D_R}{H}) \qquad \text{(eq 1-14)}$$

where R_A is the anode-to-electrolyte resistance, p is the electrolyte resistivity, D_R is the diameter of the anode circle in feet, D_A is the diameter of the anode wire in feet, and H is the depth below the high water level in feet.

Experience has shown that the diameter of the anode wire circle (D) should be typically between 40 and 70 percent of the tank diameter.

Wire resistance (R_W) is the sum of both the rectifier-to-anode lead and the rectifier-to-protected-structure lead.

$$R_W = \frac{L_W \ R_{MFT}}{100 \ ft} \qquad \text{(eq 1-15)}$$

where L_W is the length of wire in thousands of feet and R_{MFT} is the resistance of the wire in ohms per 1000 ft.

The structure-to-electrolyte resistance (R_C) is dependent primarily on the condition of the coating.

$$R_C = \frac{R_S}{A} \qquad \text{(eq 1-16)}$$

where R_S is the coating resistance in ohm-square feet and A is the total surface area. If the structure surface is bare, negligible resistance is assumed (R_C = 0).

g. Calculate required rectifier voltage and current.

The required rectifier voltage (V_{REC} and maximum current rating should include at least an extra 20 percent to allow for variations in calculations from actual conditions and for changes in the system over the system's life.

$$V_{REC} = (I) \ (R_T) \ (1.2) \hspace{3cm} \text{(eq 1-17)}$$

where I is the total current required and R_T is the total circuit resistance as calculated above.

$$I_{REC} = (I) \ (1.2) \hspace{4cm} \text{(eq 1-18)}$$

where I is the total current required and I_{REC} is the minimum current rating for a rectifier for this particular application.

Select a rectifier with DC voltage and current capacity of a slightly larger size (as calculated above) from the cathodic protection rectifier manufacturer's published literature.

h. Prepare life cycle cost analysis.

The life cycle cost analysis should be prepared according to the guidelines given in TM 5-802-1 (reference 9). Another source of information on performing life cycle cost analyses is NACE RP-02-72 (reference 21). The choice of a particular anode type and configuration for design calculation is somewhat arbitrary. The economics may dictate switching to a different design configuration and repeating the applicable design steps.

i. Prepare plans and specifications.

Prepare plans that show the protected structure, locations of anodes, rectifier, test stations, and power source, wire routing, and details of wire-to-structure connections, building or structure penetrations, wire color coding, potential survey test points in paved areas, and other pertinent information. Prepare a one-line diagram to show the entire system including wire sizes, anode type(s), power circuit, power circuit protection, and source of

power. Prepare specifications to describe required features
of the system components.

1-3. References.

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tional corrosion control techniques, and particular requirements of
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